Adaptation for life: a review of neonatal physiology

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Abstract

The neonatal period (first 28 days of life or 44 weeks postconception age) is a period of the most dramatic and rapid physiological changes seen in humans. They vary from the immediate changes in the respiratory and cardiovascular systems to a gradual maturation of the hepatic, haematological and renal systems. These adaptations support life during the development from intrauterine physiology to adult physiology. This article describes neonatal physiological changes in a system-based approach, including the changes that may extend beyond the neonatal period.

Keywords Cardiovascular changes; fetal haemoglobin; fluid balance; neonatal adaptation

Royal College of Anaesthetists CPD matrix: 1A01

Learning objectives

After reading this article, you should be able to understand the physiological changes which take place following birth and appreciate the unique aspects of neonatal physiology including:

- limited reserve capacity for temperature control, cardiovascular and respiratory function
- variable and individualized fluid requirements
- implications of hepatic and renal immaturity.

The respiratory system

The fetal respiratory system

Lung development begins by the third week of gestation and the tracheobronchial tree up to the level of terminal bronchioles is completed by week 16. However, type I and II pneumocytes are distinguishable only by 20–22 weeks and surfactant is present only after 24 weeks, making this the watershed time for pulmonary gas exchange and therefore extra-uterine survival. Surfactant production can be increased after 24 weeks by giving betamethasone to the mother, thereby improving neonatal lung function if premature delivery is anticipated. Alveolar development continues after birth, increasing fivefold in number to 300 million by 5–6 years of age. The pulmonary vasculature including the alveolar capillary membrane develops from the 16th week of gestation onwards and further remodelling of the capillary bed continues beyond 36 weeks of gestation into late childhood. The fetal pulmonary vasculature is exquisitely sensitive to hypoxia and the relatively low arterial pO_2 in utero helps to keep these vessels constricted, diverting the cardiac output to other areas like the brain. Less than 10% of cardiac output reaches the lungs and the gas exchange in fetal life is carried out by the placenta.

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The first breath

The fetal lung fluid production starts to slow down during late gestation in preparation for birth. At the start of labour, a significant amount of this fluid gets reabsorbed in response to the catecholamine surge (Table 1). The coordinated first breath is initiated centrally due to arousal from sound, temperature changes and touch associated with delivery. Central chemoreceptors stimulated by hypoxia and hypercarbia further increase respiratory drive.

The initial breaths generate high negative inspiratory pressures to facilitate lung expansion by overcoming:

- airways resistance
- viscosity of the remaining fluid in the airways
- surface tension of the air/fluid interface in the alveolus.

Alveolar distension, cortisol and epinephrine further stimulate type II pneumocytes to produce surfactant and reduce alveolar surface tension, facilitating lung expansion. Negative inspiratory pressures of up to 70–100 cm H_2O are initially required to expand the alveoli (Laplace's relationship $P = 2\ T/R$; where P is the pressure across the alveolar wall, T is the tension in the alveolar wall surface fluid, and R is the radius of the alveolus).

As the alveoli expand, the alveolar radius increases and the wall tension of the alveolus falls. Exogenous surfactant is administered to preterm neonates to reduce alveolar wall tension and facilitate mechanical ventilation. Expiration is initially active, with pressures of 18–115 cm H_2O generated,[1] forcing amniotic fluid from the bronchi. Lung expansion and increased alveolar oxygen content reduce pulmonary vascular resistance, increasing blood flow and initiating the cardiovascular changes described later.

Neonatal lung mechanics

A marked imbalance exists between chest wall rigidity and elastic recoil of neonatal lungs. The chest wall is highly compliant, offering little support to the poorly compliant lungs thus facilitating airway collapse. These two factors increase closing capacity to the point of exceeding functional residual capacity (FRC) until the age of 6. To counteract this, neonates produce positive end expiratory pressure (PEEP) via high resistance nasal airways and partial closure of the vocal cords.

Inspiratory reserve volume is limited by a flatter diaphragm and more horizontal ribs. Therefore, an increase in minute volume must be achieved by an increase in respiratory rate. The increased work of breathing imposed upon the neonate by fast

Normal pulmonary function and cardiovascular values

Measurement	Preterm neonate	Term neonate	Adult
Total lung capacity (ml/kg)	55–70	55–70	80–85
Tidal volume (ml/kg)	5–7	5–7	7
Functional residual capacity (ml/kg)	20–25	27–30	30
Vital capacity (ml/kg)	35–40	35–40	60
Respiratory rate (breaths/min)	30–50	30–50	12–16
Alveolar ventilation (ml/kg/min)		100–150	60
	Term neonate	**2 year old**	**Adult**
Heart rate (beats/min)	120–160	75–115	70–90
Systolic blood pressure (mmHg)	60	95	120
Diastolic blood pressure (mmHg)	35	60	80
Cardiac output (ml/kg/min)	200	100	70
Circulating blood volume (ml/kg)	90	80	70
Haemoglobin (g/dl)	16–18	10.5–13.5	12–17

The neonate has a reduced inspiratory reserve volume compared with adults, indicated by similar tidal volume and functional residual capacity values with a diminished total lung capacity. Significant increases in minute volume must be achieved by an increase in respiratory rate rather than tidal volume. The high cardiac output supplies the high metabolic demand of extra-uterine life. Systolic and diastolic blood pressures rise to 70/40 at the end of the first week and 90/50 by 6 months, under the control of the maturing sympathetic nervous system.

Adapted from Rennie JM, Robertson NRC, eds. A manual of neonatal intensive care, 4th edn. London: Hodder Education, 2002.

Table 1

breathing rates can quickly lead to respiratory fatigue as the diaphragmatic and intercostal muscles lack type 1 oxidative fibres.

Gas exchange across the alveolar membrane is immature in neonates, with a total shunt estimate of 24% of the cardiac output at birth, reducing to 10% of cardiac output at 1 week.[1] This rapid reduction in shunt fraction improves arterial oxygenation and reduces the effort of breathing. Neonatal lung mechanics have significant implications during anaesthesia. The effective FRC is reduced, as physiological PEEP and intercostal muscle tone is lost. These factors, together with an increased shunt fraction and high metabolic rate (6–8 ml of O_2/kg/minute), contribute to a potential rapid desaturation in neonates under anaesthesia.

Control of ventilation

Respiratory rhythm is generated in the ventrolateral medulla, and modulated by central chemo receptors in response to carbon dioxide, pH and oxygen content in the blood. Peripheral chemo receptors in the aorta and carotid bodies are functional at birth but are initially silent because of high blood oxygen content after delivery. Receptor adaptation occurs over 48 hours, permitting an appropriate response to the higher oxygen tension. The neonatal response to hypoxia is characterized by an initial increase in ventilation followed by a decrease in ventilation, reverting back to a fetal response. Ventilation changes to hypoxia alter with neonatal temperature, level of arousal and maturity. The response to hypercarbia is the same as in adults, but is more rapid because of a lower resting carbon dioxide tension.

All neonates can show a periodic breathing pattern defined as an apnoea of less than 5 seconds, often followed by tachypnoea. Premature neonates may exhibit apnoeic episodes of more than 15 seconds or a shorter period associated with a fall in heart rate. This temporary loss of central respiratory drive improves with maturity[2] but may persist up to 60 weeks post-conception age.

Cardiac changes

The fetal circulation

Oxygenated placental blood is preferentially delivered to the brain, myocardium and upper torso, with lower oxygen tension blood distributed to the lower body and placenta. Preferential splitting is achieved via intracardiac and extracardiac shunts that direct blood into two parallel circulations (Figure 1). Oxygenated blood returning from the placenta divides equally to pass either through the liver or via the ductus venosus to reach the inferior vena cava. Oxygenated blood from the ductus venosus remains on the posterior wall of the inferior vena cava, allowing it to be directed across the foramen ovale into the left atrium by the Eustachian valve. This oxygenated blood then passes through the left ventricle and aorta to supply the head and upper torso. Deoxygenated blood returning from the superior vena cava and myocardium via the coronary sinus is directed through the right ventricle and into the pulmonary artery. Most of this blood is returned to the descending aorta via the ductus arteriosus; however, approximately 8–10% of total cardiac output passes through the high-resistance pulmonary circulation. Blood in the descending aorta either supplies the umbilical artery to be reoxygenated at the placenta or continues to supply the lower limbs. The fetal circulation therefore runs in parallel, the left ventricle providing 35% and the right 65% of cardiac output. Fetal cardiac output is therefore measured as a combined ventricular output (CVO).